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Theoretical Model of Flame Propagation Through Dry Biomass Particles in a Fixed Bed

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Abstract: A theoretical analysis of the flame propagation speed in a fixed bed of burning biomass particles is presented. This analysis is based on a situation in which the reaction front moves in the opposite direction of the gas flow through the fixed bed. For this purpose, the energy conservation equation is solved for both oxidizer gas, moving against the combustion wave and solid fuel and consequently, an analytical expression for predicting the reaction front is derived. This model can be used for determining the effects of biomass particle type, inlet air flow velocity into a fixed bed and bed porosity on the reaction front speed. Finally, the propagation rate is obtained for a specific particle composed of spruce and pine. It is declared that the estimated result from the present model for the propagation rate demonstrates the reasonable compatibility with the published experimental data.

Key words: Analytical Solution · Biomass Particles · Reaction Front Speed · Fixed bed

INTRODUCTION

Dust explosions are the phenomena that flame propagates through dust clouds in air with increasing degree of subdivision of any combustible solids. They have been a recognized threat to humans and property for the last 150 years [1].

In spite of significant efforts to obtain information on the explosibility of dusts, the fundamental mechanisms of flame propagation in dust suspension have not been sufficiently studied [2]. Bidabadi and Rahbari [3] analytically investigated the flame propagation through organic dust particles and explored the flame structure mechanism and the effect of temperature difference between gas and particle on the combustion characteristics. In another study, Bidabadi and Rahbari [4] presented a novel analytical model for predicting the heat loss and Lewis number effects on the combustion of dust particles. Furthermore, in the previous study [5], the aspects of flame propagation and the structure of combustion zone were analytically investigated and the effects of different Lewis and Damköhler numbers and the initiation of particles vaporization on the combustion phenomenon of the organic dust particles were completely specified.

Among organic dust particles, biomass is the fourth largest source of energy. It supplies about 11-12% of world's primary energy consumption [6]. Biomass combustion is the main technology route for bioenergy, responsible for over 90 percent of the global contribution to bioenergy. The selection and design of any biomass combustion system is mainly determined by the characteristics of the fuel to be used, local environmental legislation, the costs and performance of the equipment necessary or available as well as the energy and capacity needed (heat, electricity) [7].

Some researchers evaluated the combustion of municipal solid waste (MSW) or biomass in full-scale grate furnaces [8,9]. However, most researchers used laboratory scale fixed-bed units to simulate operation in grate furnaces [10–12], because it is difficult and expensive to obtain detailed in-bed data from full-scale furnaces. Furthermore, experimental and simulated results showed that an analogy exists between combustion in a fixed bed and on a grate [13]. Fig. 1 shows the analogy between a fixed bed and the bed in a moving grate furnace. The analogy shows that results from fixed-bed combustion can be applied as a good approximation of moving-bed combustion due to the relatively small horizontal gradients (compared to the vertical) in

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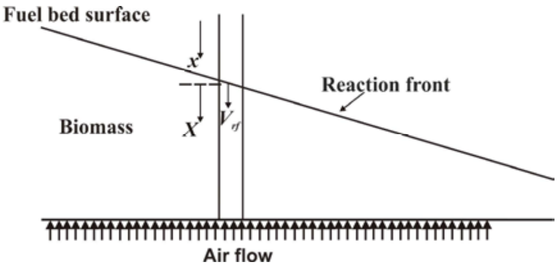

Fig. 1: Analogy between combustion in a fixed bed and on a grate

industrial facilities. The similarities may include: the bed temperature profiles, combustion rates and efficiency and, gas release from bed surface [14].

Several experimental and theoretical studies of the combustion of coal or wood particles in a fixed bed are reported recently [15-16]. However, the parameters governing the combustion of solids in a bed, such as the effects of particle size, heat and mass transfer in porous media and the interference between the solid- and gas-phase reactions, are not fully understood [11].

Propagation of the ignition flame front is one of the main research topics in the solid fuel combustion in packed beds; it determines the volatiles release rate and affects the combustion thermal output from a given grate area and the stability of combustion [13]. The ignition and propagation of a reaction front in a packed and fluidized bed biomass combustion has been studied experimentally and theoretically in the last decade [8,10,12,17,18].

Saastamoinen *et al*. [19] presented a model for ignition wave propagation and release of volatiles in beds of wood particles. In this model, moisture; bed density and air rate vary and the geometrical factors, such as particle shape, size and orientation were lumped to a single experimental parameter for heat transport in the bed. It was found out that the main factors affecting the ignition velocity were fuel moisture content, fuel volatile content, air flow rate through the bed, air temperature, bulk density of the fuel bed, particle size and particle shape.

Recently, Bidabadi *et al*. [20] analytically investigated the effects of radiation and particle size on the pyrolysis of biomass particles. The overall investigation of this study led to a novel non-linear burning velocity correlation. Consequently, the impacts of radiation and particle size on the combustion properties of biomass particles were declared in that research.

In this paper, the flame propagation in a fixed bed of burning biomass particles is studied. After ignition, a reaction front propagates downwards from the surface of the bed against the direction of the combustion flow. The generated heat in the reaction front is transported against the flow of combustion air and, therefore, dries and devolatilises the biofuels which allows the reaction front to propagate. In this research, the study done by Saastamoinen *et al*. [10] is developed by adding the conduction and radiation effects into the governing equations. The results can also be applied to traveling grates, where the fuel is ignited on top of the bed and the air flows upwards through the grate and the bed.

Mathematical Model: The energy conservation equations for the oxidizing gas flow and the solid fuel in the bed are described by the following equations:

$$\begin{gathered}\rho_g c_g V_g \frac{\partial T_g}{\partial x} = \frac{\partial}{\partial x}(\lambda_g \frac{\partial T_g}{\partial x}) + hS(T_p - T_g) \\ (1-\varepsilon)\rho_p c_p \frac{\partial T_p}{\partial t} = \frac{\partial}{\partial x}(\lambda_{eff} \frac{\partial T_p}{\partial x}) - hS(T_p - T_g) + \dot{q}\end{gathered} \tag{1}$$

Where h, S and $\dot{q}$ are the convective heat transfer coefficient, volumetric solid surface area and rate of heat generation per unit volume, respectively.

In the model presented here, it is assumed that the local absorption of energy in the bed is directly proportional to the local heat flux. The heat flux from the burning particles through the bed exponentially decays with distance, $q'' = q''_0 \exp(-\alpha X)$. This heat flux expression gives the local heat generation $\dot{q} = \alpha q''_0 \exp(-\alpha X)$ [10].

The radiative heat flux depends on the effective temperature of the flame zone T_f and is defined by $q''_0 = K\sigma T_f^4$, where $k(<1)$ is the effective radiation coefficient and λ_{eff} is the effective thermal conductivity of particles consisting of conductive and radiative constituent:

$$\lambda_{eff} = (1 - \varepsilon)\ \lambda_p + 4\varepsilon\sigma d_p\ T^3_p \tag{2}$$

Where ε, σ, d_p, T and λ_p are the bed voidage, Stefan–Boltzmann constant, particle diameter, temperature and thermal conductivity of the fuel, respectively [18].

Analytical Solution: A coordinate system X attached to the reaction zone is introduced as follows:

$$X = x\text{-}\chi(t) \tag{3}$$

Where $\chi(t)$ is the position of the reaction zone and thus, $V_{rf} = \chi'(t)$ is the reaction front velocity. Applying this moving coordinate results in a new system of governing equations as:

$$\dot{m}''_g c_g \frac{\partial T_g}{\partial X} = \lambda_g \frac{\partial^2 T_g}{\partial X^2} + hS(Tp - Tg) - (1-\varepsilon)\rho p^c p^V rf \frac{\partial T_p}{\partial X} = \lambda_{eff} \frac{\partial^2 T_p}{\partial X^2} - hS(Tp - Tg) + \dot{q} \tag{4}$$

Where λ_g and λ_{eff} are constants. The dimensionless parameters are defined as below:

$$\xi = \frac{hS}{\dot{m}''_g c_g} X = \alpha \Lambda X \quad and \quad \Lambda = \frac{hS}{\alpha \dot{m}''_g c_g} \quad and \quad \dot{q} = \alpha q''_0 e^{-\alpha X} = \alpha q''_0 e^{-\xi/\Lambda} \quad and \quad T^*_p = \frac{T_p - T_\infty}{T_{ig} - T_\infty}$$

$$T^*_g = \frac{T_g - T_\infty}{T_{ig} - T_\infty} \quad and \quad V^*_{rf} = \frac{(1-\varepsilon)\rho_p c_p V_{rf}}{\dot{m}''_g c_g} \quad and \quad \beta_g = \frac{\lambda_g hS}{(\dot{m}''_g c_g)^2} \quad and \quad \lambda^* = \frac{\lambda_{eff}}{\lambda_g} \tag{5}$$

$$\beta_p = \frac{\lambda_{eff} hS}{(\dot{m}''_g c_g)^2} = \lambda^* \beta_g \quad and \quad \varphi = \frac{\alpha q''_0}{hS(T_{ig} - T_\infty)}$$

Equation (4) is represented in dimensionless form as follows:

$$\begin{aligned} &\beta_g \frac{d^2 T^*_g}{d\xi^2} - \frac{dT^*_g}{d\xi} + T^*_p - T^*_g = 0 \\ &\lambda^* \beta_g \frac{d^2 T^*_p}{d\xi^2} + V^*_{rf} \frac{dT_{p*}}{d\xi} - T^*_p + T^*_g + \phi e^{-\xi/\Lambda} = 0 \end{aligned} \tag{6}$$

The following expression is obtained for the dimensionless gas temperature by eliminating T^*_p between the above equations.

$$\lambda^* \beta_g^2 \frac{d^4 T^*_g}{d\xi^4} + (V^*_{rf} - \lambda^*)\beta_g \frac{d^3 T^*_g}{d\xi^3} - (V^*_{rf} + \lambda^* \beta_g + \beta_g)\frac{d^2 T^*_g}{d\xi^2} - (V^*_{rf} - 1)\frac{dT^*_g}{d\xi} = \phi e^{-\xi/\Lambda} \tag{7}$$

Equations (7) is solved for obtaining the dimensionless gas temperature as:

$$T^*_g = \frac{\phi \Lambda^4}{(V^*_{rf} - 1)\Lambda^3 - (V^*_{rf} + \lambda^* \beta_g + \beta_g)\Lambda^2 - (V^*_{rf} - \lambda^*)\beta_g \Lambda + \lambda^* \beta_g^2} e^{-\xi/\Lambda} \tag{8}$$

Replacing equation (8) into (6) results in the dimensionless particle temperature as follows:

$$T^*_p = \frac{\phi \Lambda^2 (\Lambda^2 - \Lambda - \beta_g)}{\eta} e^{-\xi/\Lambda} \tag{9}$$

As known, the particle temperature is equal to the ignition temperature at î=0, so dimensionless particle temperature $T^*_p = 1$, therefore:

$$V^*_{rf} = \phi \Lambda + \frac{(\lambda^* + 1)\beta_g \Lambda^2 - \lambda^* \beta_g \Lambda - \lambda^* \beta_g^2 + \Lambda^3}{\Lambda^2 - \Lambda^2 - \beta_g \Lambda} \tag{10}$$

Therefore, velocity in dimensional form is:

$$V_{rf} = \frac{1}{(1-\varepsilon)\rho_p c_p}\left(\frac{q''_0}{T_{ig} - T_\infty} + \frac{hS(\lambda_g \alpha + \dot{m}''_g c_g)}{hS - \alpha \dot{m}''_g c_g - \lambda_g \alpha^2} + \lambda_{eff} \alpha\right) \tag{11}$$

RESULTS

This model can be used as a proper approach to study the influence of combustion characteristics, such as biomass species, particle diameter and density, air temperature and flow velocity on the flame front velocities. The propagation rate of the reaction front (i.e.,$(1-\varepsilon)\rho_p$) is defined as the apparent density (i.e.,$(1-\varepsilon)\rho_p$) multiplied by the reaction front velocity.

A wooden particle which is a mixture of spruce and pine, almost dry (2.1% wet basis) with 30 mm diameter and the dry bed density of 230 kg/m^3, is selected in order to compare the theoretical reaction velocity and associated experimental data [19]. From [10], the ambient temperature, the ignition temperature, the effective radiation temperature T_f and effective radiation coefficient K for this type of particle are $T_{,\infty} = 293k$ $T_{ig} = 650k$, $T_f = 903.2 + 5547\,\dot{m}_g''^2$ and $K = 0.819 - 2.100\,\dot{m}_g''$, respectively.

Fig. 2 shows the propagation rate profile of the reaction front as a function of air flow rate both with and without radiation effect. As seen in the experimental and obtained results, the ignition flame front rate goes up and down with the increase in the air-flow rate. From this figure, the estimated result demonstrates a reasonable compatibility with the associated experimental data.

Fig. 3 illustrates the effects of pre-heating the primary air on the propagation rate of the reaction front. The model indicates that the propagation rate increases with increasing the primary air preheating temperature. In addition, radiation has a remarkable effect on the propagation rate and causes the increase in this rate.

Conduction and radiation are the main modes of energy transfer from particles which are lumped into an effective thermal conductivity and play an important role in propagation of the ignition front. In reality, the solid conductivity may deviate from the predicted value at temperatures below the pyrolysis temperature [14]. Fig. 4 demonstrates that the propagation rate increases with increasing the value of the effective thermal conductivity.

The porosity is a packing property of the bed material and is calculated from the volumetric shrinkage of the particle and should not be mixed up with the porosity of the fuel. Change of the porosity would affect the pressure drop across the solid bed, which significantly influences the air supply rate [21]. The porosity of the fuel influences the reactivity (mass loss per time unit) of the fuel and thereby its devolatilisation behavior [7]. Fig. 5 shows that the increase in the porosity of bed results in increasing the propagation rate of the reaction front.

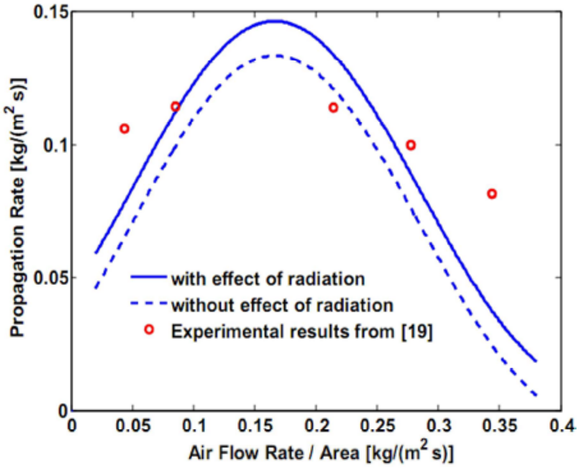

Fig. 2: Measured and calculated propagation rate of the reaction front for different air flow rates

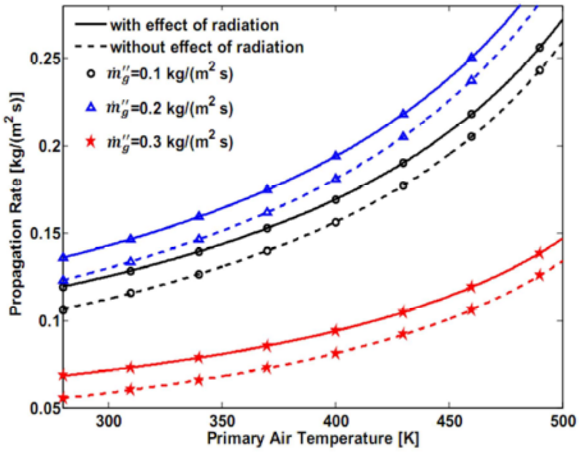

Fig. 3: Effect of primary air temperature on the propagation rate of the reaction front

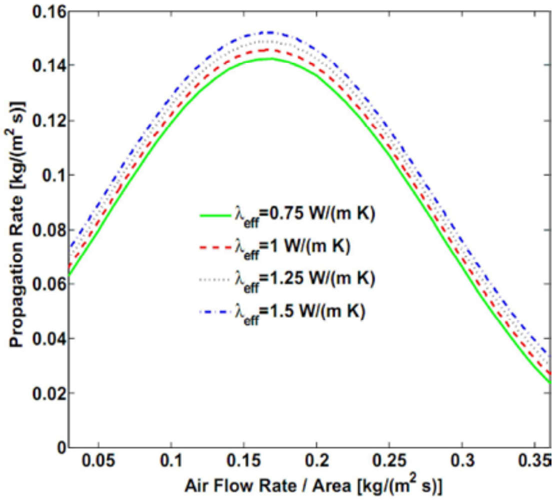

Fig. 4: Effect of the effective thermal conductivity on the propagation rate of the reaction front

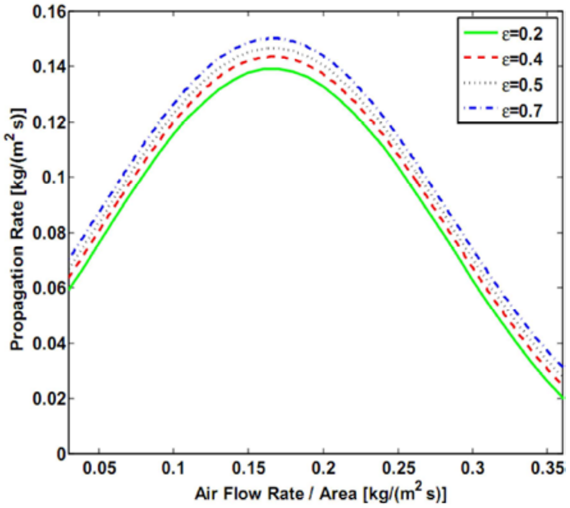

Fig. 5: Effect of the bed porosity on the propagation rate of the reaction front

CONCLUSION

This paper presents a model for biomass combustion process in fixed bed for calculation the propagation rate of reaction front in a fixed bed combustor. This analysis shows that the main factors affecting the reaction velocity for dry biomass particles are fuel volatile content, air flow rate through the bed, primary air temperature, bulk density of the fuel bed and properties of particles. The obtained results indicate that the velocity of the reaction front goes up and down with increasing the air velocity, first reaching a maximum value and then decreasing slightly until the reaction extinguishes. The model prediction indicates that the reaction velocity is sensible to primary air temperature, the effective thermal conductivity and bed porosity. Consequently, the propagation rate of the flame front attained by the present model both with and without radiation effect is compared with the published experimental data and it is revealed that the achieved propagation rate has a reasonable compatibility with the experimental data.

Nomenclature:

c	Specific heat, J/(kg K)	*Greek symbol*	
d	Diameter, m	α	Decay coefficient, m^{-1}
h	Convective heat transfer coefficient, W/(m^2 k)	β	Defined in Eq. 5 $\beta = \lambda hS/(\dot{m}''_g c_g)^2$
K	Effective radiation coefficient	ε	Porosity of the bed
$\dot{m}''$	mass flux, kg/(m^2 s)	Λ	Defined in Eq. 5
$\dot{q}$	Rate of heat generation per unit volume, W/m^3	λ	Thermal conductivity, W/(m K)
q''	heat flux, W/m^2	λ^*	Dimensionless thermal conductivity, $\lambda^* = \frac{\lambda_{eff}}{\lambda_g}$
q''_0	Heat flux at reaction front, $q''_0 = K\sigma T^4_f$	ξ	Dimensionless coordinate, $\xi = hSX/(\dot{m}''_g c_g)$
S	Volumetric solid surface area, m^2/m^3	ρ	Density, kg/m^3
T	temperature, K	σ	Stefan-Boltzmann's constant, 5.67×10^{-8} W/(m^2 K^4)
T^*	Dimensionless temperature, $T^* = (T - T_\infty)/(T_{ig} - T_\infty)$	ϕ	Defined in Eq. 5 $\phi = aq''_0/(hS\,(T_{ig} - T_\infty))$
t	time, s	*Subscripts*	
V	velocity, m/s	0	At reaction front
V^*	Dimensionless velocity, $V^* = (1-\varepsilon)\rho_p \rho_p V/(\dot{m}''_g c_g)$	∞	Far from reaction front
X	coordinate, m	eff	effective
X	moving coordinate, m	g	gas
		re	reaction
		rf	reaction front
		p	particle

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